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Office of Naval Research
Overview of Corrosion S&T Program

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Report Documentation Page

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Impact of Corrosion on the Navy

Corrosion: Navy’s No. 1 Maintenance Problem

***The Annual Cost of Corrosion for Army Ground Vehicles and Navy Ships, LMI Report, Apr., 2006**

****Cost obtained using FY06 data – Under Service Review**
Combined cost of the Navy and USMC aircraft

Changing Requirements

The Evolutionary Approach ...   10 Yrs   20 Yrs

Future Ships & Vehicles

Present

Naval Power 21

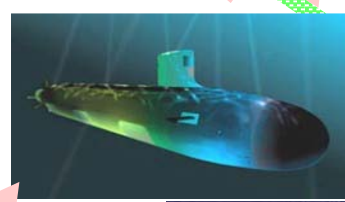
- Faster, Maneuverable Ships for Littoral Operations
- Extended Operating Cycles
- Reduced Manning
- Expeditionary Maneuver from the Sea

Traditional & Non-traditional Materials

High Performance Oriented
Lighter, Faster Ships

Combat Systems
Fuel Cells & Batteries

Aluminum
Composites



New Sets of Corrosion Issues

2020

Classic Response to Naval Corrosion

....Chip
Scrape
Paint
Wash...

Some Solutions to these Problems

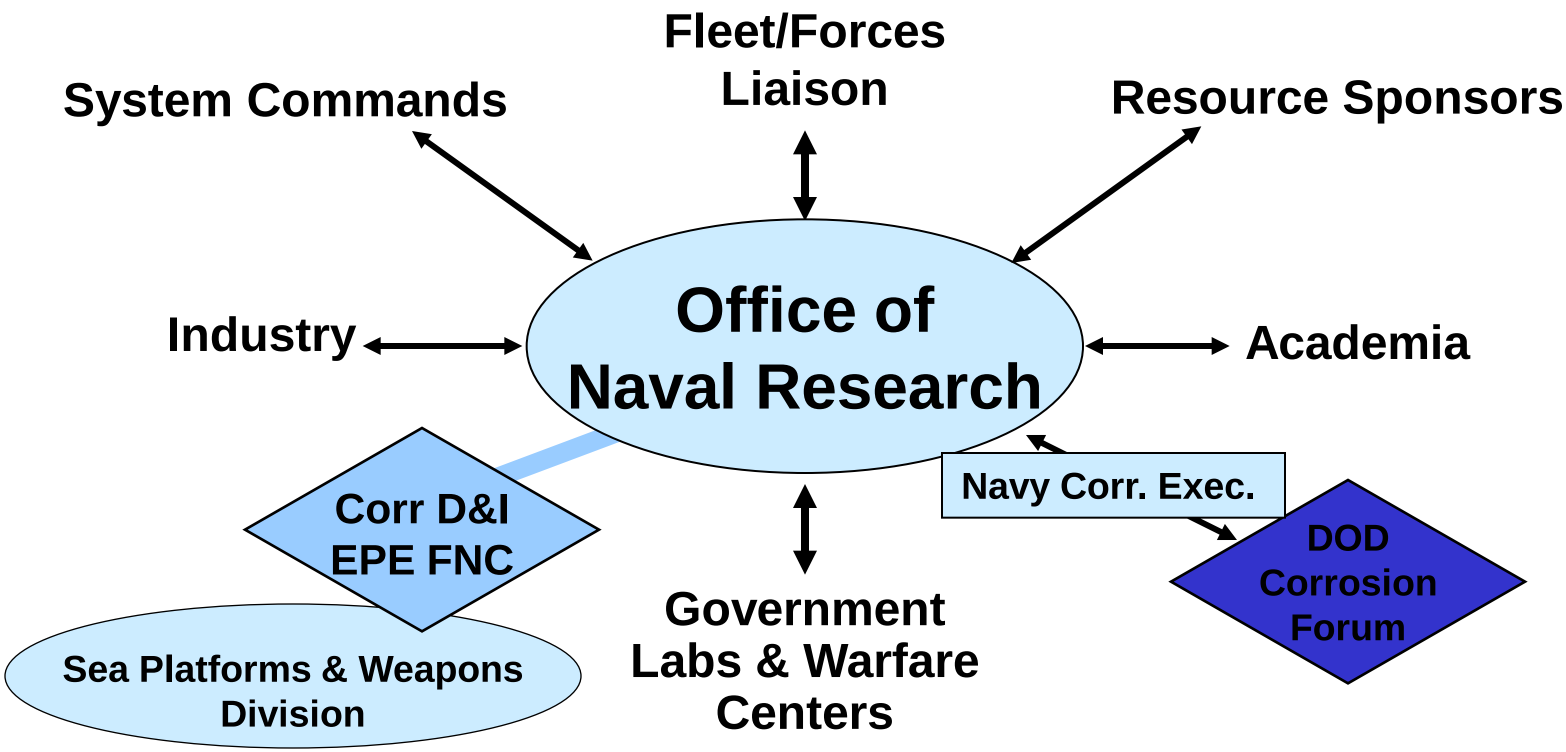
- Improved materials
- High Performance Coatings and Application
- Better inspection/detection methods and NDI
- Better treatment methods and technologies
- Smart Design and Engineering
- Improved Processes and Education

Science & Technology

★ Bottom line:
Up front prevention leverages downstream savings

The Navy Corrosion S&T Community

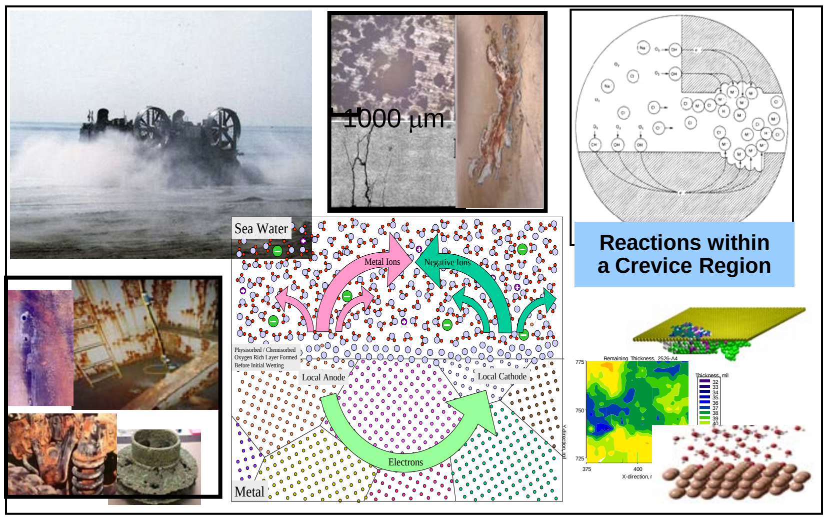
- ONR provide a full spectrum of basic and applied R&D to advanced technology demonstration and implementation



Corrosion Control Technologies

Vision: Develop corrosion control and prevention technologies and processes

- ♦ to reduce Navy operation and maintenance cost
- ♦ to extend service life of Navy assets beyond original design
- ♦ to meet design requirements for future Navy and USMC platforms



Description:

Develop corrosion resistant alloys and coatings, and corrosion control and prevention technologies to mitigate corrosion and its effects under sea water and marine environment

- **Approach:**
- Understand science-based corrosion mechanisms and processes
- Develop HP advanced/novel coatings
- Develop multi-scale corrosion models
- Develop corrosion mitigation/repair technologies

Trust Area 1: Understanding of corrosion mechanism and processes

Thrust Area 2: Development of corrosion model

Thrust Area 3: Development of HP marine coatings

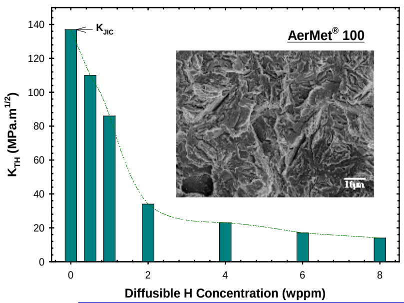
Trust Area 4; Development of diagnostics technologies

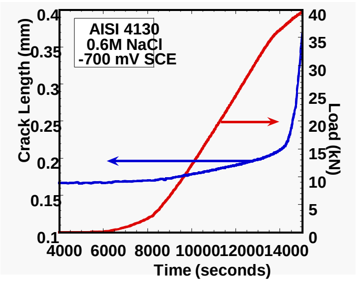
Corrosion Related
Discovery and Invention (D&I)

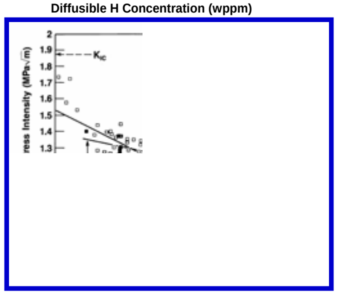
Develop Materials and Technologies Resistant to Sea Water and/or Marine Atmosphere

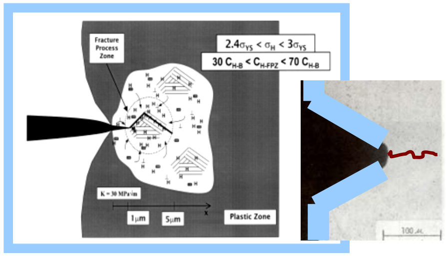
- Mechanistic study of corrosion in naval materials/structures
  - Hydrogen embrittlement in ultra-high strength steels (UHSS)
  - Low temperature carburization
- Advanced coatings technology
  - Universal coating and/or application specific/problem solving/ high-performance coatings
  - Environmentally safe coatings
- Science based “corrosion model”
  - Study of materials, environment/ operation, degradation mechanism, processes
  - Prediction of materials performance/service life
  - Corrosion protection of marine grade Al alloys
- Sensors and processes
  - Intelligent corrosion sensor systems to provide corrosion assessment and life-cycle diagnostics

Hydrogen Assisted Cracking in High Strength Alloys for Marine Applications









Issue:

H assisted cracking is key failure mode for high performance materials in marine environments

Objective:

Establish and validate quantitative-predictive models of hydrogen cracking of high strength alloys in marine environment to control cracking with reduced experimental characterization

Approach:

Predict K_{th} and da/dt_{II} by coupled assessment of crack tip H uptake/trapping (C_s) and continuum damage laws with material parameters input

- Enable integrated physics-based modeling with few adjustable parameters to reduce testing

Scientific/Technical Achievement:

- Predicted C_s vs. potential for AerMet 100
- Predicted and validated K_{th} and da/dt_{II} vs. potential for AerMet 100
- Quantified material and electrochemical mitigation strategies

Naval Impact:

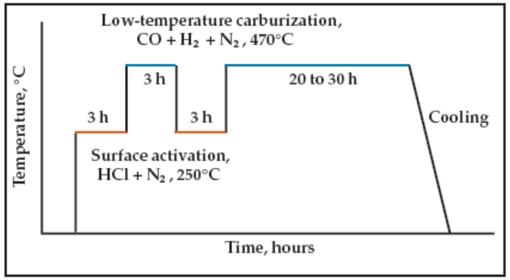
Quantitative prediction enables

- Cathodic protection optimization
- Alloy design
- Assessment of coating galvanic compatibility

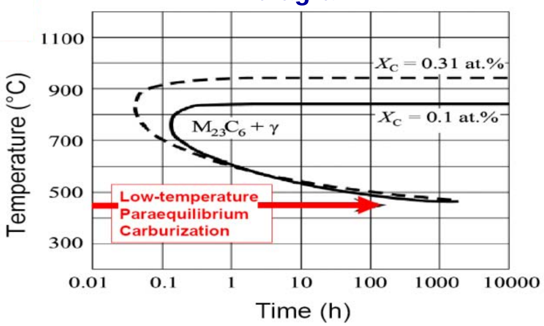
to minimize risk of premature cracking

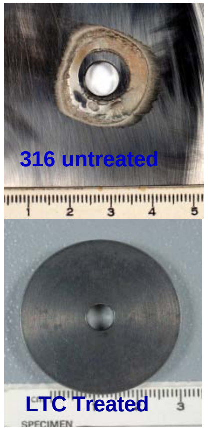
Low Temperature Colossal Supersaturation (LTCSS) Process

LTC process



TTT diagram





seawater crevice corrosion on 316 Stainless Steel

LTCSS Surface Modification:

- Carbon concentrations > 12 at. % in 316 stainless steel while maintaining single phase austenite, i.e.. no detrimental precipitates
- Treatment temperatures below 570°C, significant increases in surface hardness, wear and corrosion resistance.

Objective:

Improve the mechanical and electrochemical properties of SS by surface engineering through understanding of paraequilibrium carburization mechanism(s) that lead to the enhanced corrosion resistance

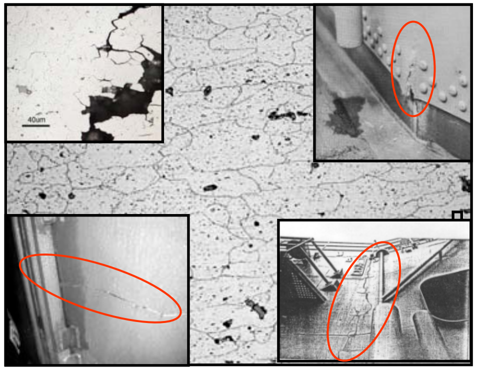
Approach:

- Determine how the passive film is modified by LTCSS treatment
- Identify the mechanism responsible for the increased corrosion performance
- Determine the effect of the LTCSS treatment on stress corrosion cracking behavior
- Determine which Naval alloys are amenable to LTC surface modification

Scientific/Technical Achievement:

- Discovery of a carbon induced passivity for LTCSS treated austenitic stainless steels
- \- Low temp. allows interstitial C diffusion, but not substitutional diffusion
- \- Hardened cases are formed and detrimental carbide formation is suppressed
- Carbon content in passive film of LTCSS treated alloys is dynamic, i.e. changes with potential

Aluminum 5XXX Alloy Program



Navy Needs:

- Corrosion resistant, light weight, high strength and affordable materials to meet faster, maneuverable ships for littoral operations
- AA5XXX alloys for high strength-to-weight ratio, weldability & corrosion resistance

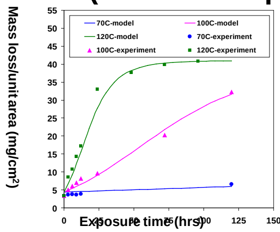
IGC; Intergranular Corrosion, IGSCC; Intergranular Stress Corrosion Cracking

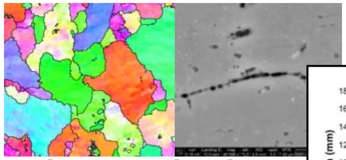
Objective:

Develop a comprehensive approach to mitigate IGC / IGSCC of sensitized AA5XXX alloys

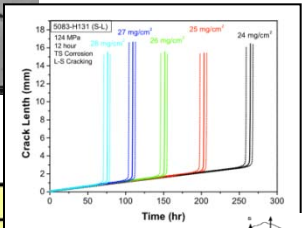
Approach:

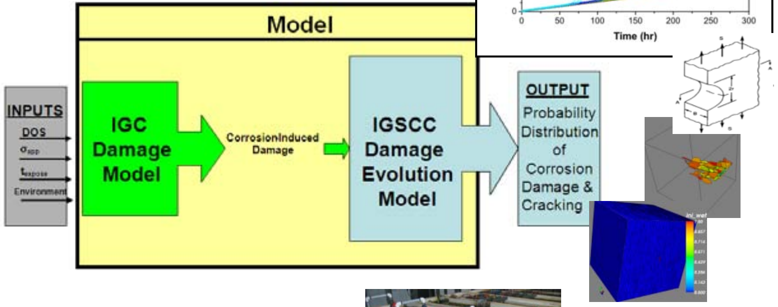
DOS f (Time & Temp)



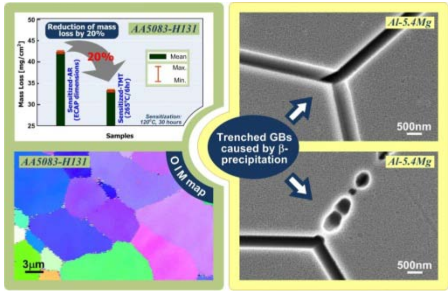


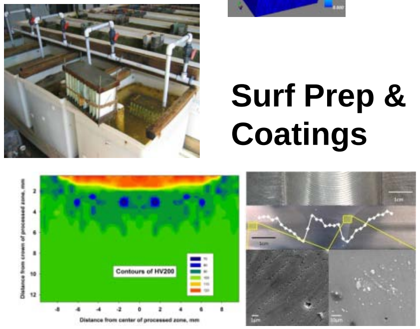
Characterization





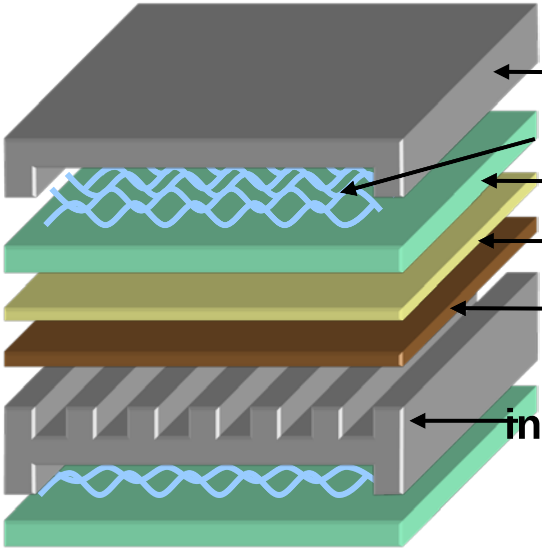
GBE





Surf Prep & Coatings

Improved Corrosion Resistance of Solid Oxide Fuel Cell (SOFC) Interconnect Materials



Issue:

Solid oxide fuel cells (SOFCs) can produce electric power very efficiently. However, materials degradation decreases the efficiency over time and limits the durability of the cells

Objective:

Enhance the durability/reliability of SOFCs by improving the corrosion resistance of the interconnects - Understanding of dual atmosphere effects, oxide volatility, and reactive element effects (REEs)

Approach:

- Develop dense coating materials by deposition of oxide films with greatly reduced Cr_2O_3 activity or a Cr-free material with low volatility to suppress evaporation
- Investigate the resistance of ferritic stainless steels to accelerated degradation in dual atmosphere conditions
- Define the mechanism of REEs on the oxidation of Ni and stainless steels

Scientific/Technical Accomplishments:

- Dual atmosphere experiments in progress
- Completed deposition of various oxides
- Analysis of the effect of CeO_2 doping on the oxidation rate of Ni and Fe-Cr alloys in progress
- Measurements of chromia evaporation rates in progress

Naval Impact:

Stealth operation, fuel flexibility and scalable power unit

Enterprise & Platform Enabler (EPE) Future Naval Capabilities (FNC)

- **Objective (Utilize the S & T)**
  - Reduce the cost of acquisition/maintenance due to corrosion and increase readiness
  - Improve performance, availability and operations
- **Approach**
  - Develop, demonstrate and transition corrosion control, monitoring, Prevention and inspection technologies for ships, aircraft, vehicles and facilities
  - Focused on the Fleet transition of technologies
- **Technologies**
  - **EPE-FY04-02 (FNC Total Ownership Cost Reduction)**
    Coatings, Corrosion Preventative Compounds, Sensors, NDI Technologies
  - **EPE-FY08-09 (EC Maintenance Reduction Technologies)**
    Topside coatings, Nonskid coatings, Rudder coatings
  - **EPE-FY10-03 (EC Corrosion and Corrosion Related Signature Technologies for Increased Operational Availability)**
    Corrosion/Signature diagnostic sensors and models, innovative robust corrosion control components and systems
  - **EPE-FY12-01 (EC Corrosion Mitigation Technologies and Design Integration**
    Sprayable damping systems, corrosion resistant surface treatment, design modules for corrosion prevention

Success Story: Rapid Cure Single Ship Tank Coatings (EPE-FY04-02)

Product Description

Rapid cure single coating systems for enhanced corrosion control in shipboard tanks and voids to reduce application time and cost

Warfighter Payoff

- NPV $250M / 40-yr service life
  - Extension of platform service life
  - ~35% reduction in tank and void painting cost, 40% reduction in tank/void preservation time, material cost equal to legacy systems

Fleet Transition

- Demonstrated in more than 65 tanks on amphibious ships, carriers and submarines
- Full shipyard implementation by NAVSEA05/04 n FY08 via CWP (Cumbersome Work Practices) Task Force
- Mandated via NAVSEA 05P23/294 11 Sept, 2008

Demonstration Results

Single Coat Polyurethane After 2 Years in a Fresh Water Tank

Solvent based legacy system after 1 year

Note that coating has failed heavily from extensive osmotic blistering

Solvent free rapid cure after 2 years

Light rust staining is from ships piping system and Tank level indicator, not from the tank itself

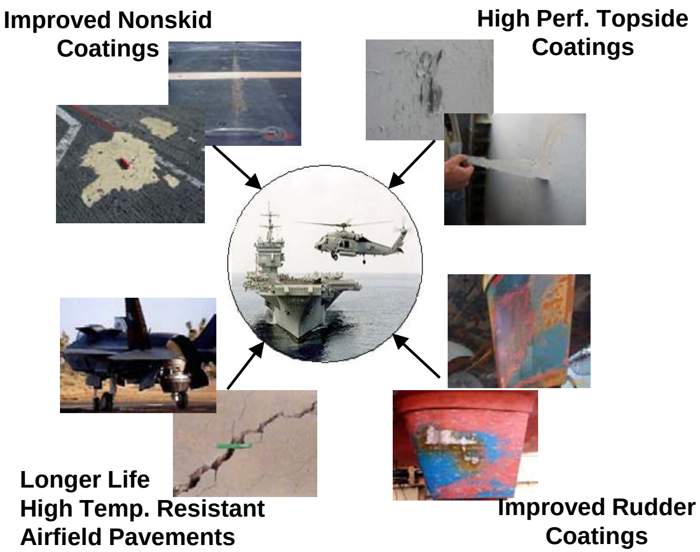
SSBN Trim Tank Application
Supported 28-day Maintenance Docking
Saved 7 days of Schedule!

Bottom Line

Rapid Cure Single Coating System : <u>35 hours</u> to Completion

Legacy System (Prime, Stripe, Topcoat) : <u>216 hours</u> to Completion

Maintenance Reduction Technologies (EPE-FY08-09)



Objective:

Extend service life of ship structures and airfield pavement by >3 times to meet extended dry dock cycle, to meet high temperature requirements for future aircraft and maintenance cost reduction by providing

- **Corrosion control and prevention technologies that prevent and mitigate corrosion and its effects**
- **Improved materials, products and processes that are environmentally compliant and cost-effective**

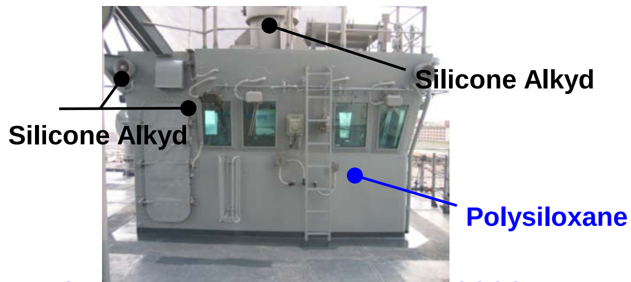
Payoffs: NPV $1052M

- **Rapid turn around**
- **Longer service life**
- **Enhanced operational readiness and safety**

*NPV (Net Present Value) based on cost analysis by NSWCCD Cost Division

Accomplishment:

- **Topside Coatings:**
  SW polysiloxane QPD qualified, 1 Feb., 2010



Coating Installed – March 2008

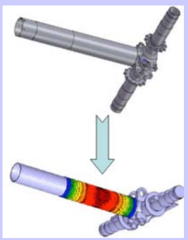
- **Non-Skid Demonstration USS WHIDBEY ISLAND (LSD-41)**

Corrosion Mitigation Technologies and Design Integration (EPE-FY12-01)

Muzzle Door Linkage Failures

Corroded aluminum pipe at bronze CMWD nozzle

Initial Design



Corrosion Risk

Galvanic Interaction at Bulkheads

Objective: Develop corrosion mitigation technologies and design modules to reduce or eliminate corrective maintenance and reduce total ownership costs

Impact if Not Addressed:

- Continued high lifecycle cost due to excessive corrosion
- Degraded mission cycle due to current system failures
- New designs without CPC (Corrosion Prevention and Control) resulting in high maintenance and repair

PROPOSED SOLUTION

- Sprayable coatings to replace damping tiles
- Corrosion and wear resistant surface treatment
- Corrosion informed design modules for commercial CAD/CAE integration

Value to Naval Warfighter:

- Reduce construction and repair costs
- Increase operational readiness
- Enhance mission capability

Partners:

- NRL, NSWCCD, PMS 397, PMS501, SEA05P, NAVAIR, USMC

Transition Sponsor: NAVSEA 05P

ONR Contact: Dr. Airan Perez,
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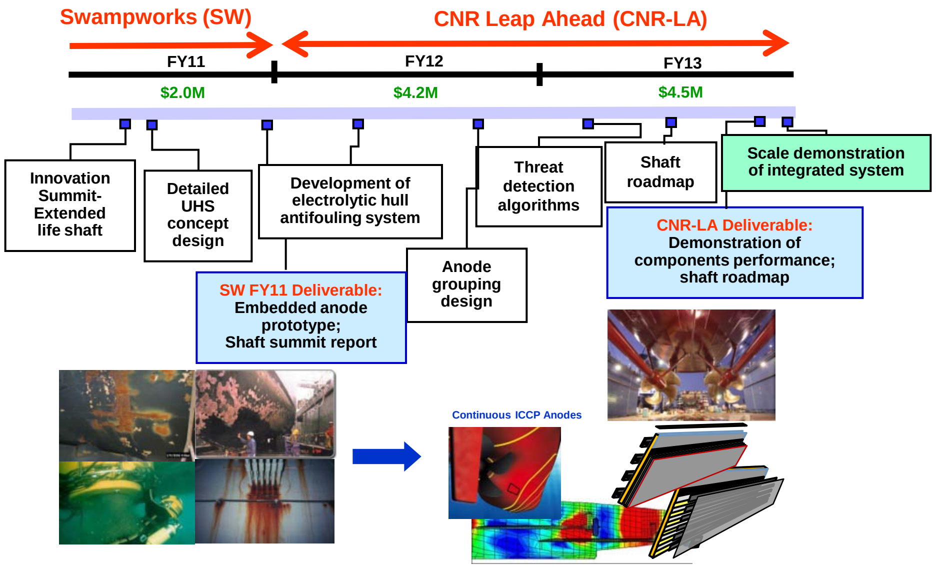
MFS Technologies: Underwater Hull Shield



Focus on Game-Changing Advances:

- Elimination of dry-docking for shaft maintenance
- Elimination of AF coatings
- Elimination of underwater hull cleaning and coating repair
- Elimination of sacrificial anode replacement

Vision:

Deliver capabilities which eliminate underwater hull maintenance and extend shaft life allowing for a single mid-life 20 year dry-dock over life of ship

Payoffs: ROI 21

Elimination of ship dry docking enabling increased Operational Availability (Ao) and reduced Total Ownership Cost

Deliverables:

- Detailed concept design of Underwater Hull Shield and Long-Life Shaft
  - Embedded Anode Prototype
  - Shaft Summit Report
- Proof of concept validation for integration of corrosion and fouling control
- ICCP system with threat detection capability

Summary

- Corrosion Prevention and Control is a top operations and maintenance priority
- High payoff ONR projects are producing viable products
- Corrosion research and development is helping:
  - Reduce O&S corrosion cost to enable fleet recapitalization and modernization
  - Extend service life of Navy assets beyond original design
  - Increase readiness for present and future missions while reducing resource requirements
  - Provide capability to meet design requirements for future Navy and USMC platforms
- Continue to investigate target areas for improvement and search for cost effective solutions

Research Opportunities:

- Understanding of corrosion mechanism
- Mechanistic modeling of corrosion damage
- Advanced smart coatings technology
- Distributed Impressed Current Cathodic Protection
- Corrosion mitigation technology

Interested Research Topic Areas

Coatings

- Non-skid coatings
- Rudder coatings

- Fundamental degradation mechanisms
- Quick (Rapid) cure
- Corrosion inhibition

- Coating repair
- Underwater-applied coatings
- Internal pipe coatings
- Non Cr based coating
- Life prediction
  - Modeling of effect of environmental factors including UV and Ozone)
- Smart coatings
  - Self-healing coatings
  - Multifunctional coatings
  - Condensation reducing coatings
  - “Trigger-release” repair (AC, AF, signature)
  - Self Healing and Self Cleaning Smart Coating

Surface tolerant (oil, moisture, contaminants)
Superhydrophobic coatings
Tailoring Surfaces for Corrosion Prevention
Conductive coatings

(H)-Environmentally Assisted Cracking

Improved diagnostics
Transition from short cracks (pits) to long cracks
Fasteners and gears and bearings
Corrosion fatigue of advanced materials

SCC in advanced materials
3D evaluation tools
Integrated Models for Structural Corrosion Reliability
Coupled Analysis (fluid-solid-electro-chemical) for Corrosion on Ship Structures

Surface Modification Technologies

Friction stir processing
LTC

MIC

Sea-Basing **Elimination of macro-biofouling**
Control of invasive species
Avoid transferring fouling species to sea-base
Mn containing biofilms
MIC detection and assessment (sensor)
MIC modeling **MIC diagnostic tools (can be used at sea)**
Accelerated bio-consumption of aluminum anodes

Impressed Current Cathodic Protection

- **Distributed ICCPs**
- **Electrolytic antifouling**

High Temperature Oxidation and Corrosion

- **Durability of Fuel Cells**
- **Minor element effects in high temperature coatings**
- **Oxide film formation and breakdown (microstructure)**
- **Sensors for high temp coatings**
- **Substrate/coatings matching/compatibility**
- **Life prediction/modeling**
- **Ceramic film growth/deposition processes for wear, high temperature and protective coatings**
- **Ceramic composite coatings**

Joining and Fabrication

- **Composite/metal joints**
  - **Interface degradation**
  - **Interface Issues**
- **Adhesives and sealants**
  - **biofuels compatibility**
- **Thick section composites (impact on metallic alloys)**
- **Repair**
- **Coating of composites**
- **Ceramic-metal joints**

Understanding of Corrosion Mechanism

- Oxide film formation and breakdown
- Understanding and modeling pitting evolution
- Understand and predict erosion/cavitation corrosion

Mechanistic Modeling of Corrosion Damage

- Modeling of Al 5XXXalloy sensitization leading to IGSCC

Sensors

- MIC detection and assessment (sensor)
- Stable, rugged reference electrodes
- Rapid detection of surface contamination
- Chlorination sensor
- Detection of corrosion/cracking on shafts
- Corrosion under paint and/or insulation
- Distributed vice point sensors

- Drain pipe/Overboard Discharge Sensors for corrosion under coatings